TRIGGERING OF TRIGATRON SPARK GAPS

F.E. Peterkin and P.F. Williams
Department of Electrical Engineering
University of Nebraska-Lincoln
Lincoln, NE 68588-0511

ABSTRACT

The trigatron has been in widespread use as a demand-triggered, high-voltage switch for more than 40 years. In spite of the popularity and maturity of the technology, there persists an uncertainty over the basic physical mechanism(s) responsible for triggering breakdown in the devices. We present the results of an empirical study which directly demonstrate that in the normal operating region of the devices breakdown is initiated by streamers launched from the trigger pin before the appearance of the trigger spark. We compare our results with those of previous workers, and discuss the generality of our conclusions. Our results also provide empirical information about the streamers.

INTRODUCTION

The trigatron spark gap was invented in the early 1940's to serve as a switch in high-power modulators for radar,[1][2] and has found wide application as a high voltage, high current switch. There is disagreement about the physical mechanism responsible for triggering breakdown of the main gap. The most common view in the technical literature is that the breakdown of the main gap is initiated after the gap between the trigger pin and the adjacent main gap electrode breaks down, and is the result of the action of this spark.[1-10] Another viewpoint, which has been gaining favor recently, is that breakdown occurs as a result of the formation of a streamer in the distorted field around the trigger pin tip before the formation of the trigger spark.[11-19]

The resolution of this long-standing controversy has important consequences for the design of trigatron spark gap switches. If the first viewpoint is correct, trigatrons should be designed so that the spark between the trigger pin tip and the adjacent main gap electrode forms as rapidly and reliably as possible, whereas under the second view the formation of this spark should be delayed at least until a streamer has formed and propagated across the gap. In this paper we present recent experimental results which clearly and directly support the second viewpoint, and clarify the detailed succession of events occurring during the initial stages of triggered breakdown. We believe our conclusions to be general and to impact directly several design questions for trigatron spark gap switches as well as other types of triggered spark gap switches.

We find that in the region of parameter space we studied (charging voltage near self-break, trigger voltage 20-50% of charging voltage, and roughly atmospheric pressure), triggered breakdown occurs through the following sequence of events. Upon arrival of the trigger pulse at the trigger pin streamers form after a short delay and propagate across the gap. One or more streamer channels then connect the trigger pin to the opposite main gap electrode through a high resistance (≈10 kΩ), and the switch is still open. The applied field causes the ionization density in these streamer channels to rise, decreasing this resistance. Concurrently the gap between the trigger pin and the adjacent main gap electrode also breaks down through a streamer/channel-heating process. The detailed sequence of events beyond this point is complex, depending on the relative timing of these two breakdown processes, the source resistance and pulse length of the trigger generator, and the main gap charging voltage. In most cases the final result is two thermalized arcs connecting the trigger pin to the opposite main gap electrode and the adjacent electrode, but other final configurations are probably possible.

We have performed experiments for N_2 fills between 250 and 900 Torr; synthetic air and H_2 fills at 700 Torr; trigger pin diameters between 0.08 and 0.5 cm; rounded, squared-off, and ring-shaped pin tips; pins flush with and recessed below the host electrode surface; charging voltages between ≈25 and 99% of static self break voltage (15-62 kV for 700 Torr N_2); trigger pulse voltages between 5 and 25 kV; and both heteropolar charging configurations (+ trigger, - main gap, and vice-versa). Except for very low charging voltages or very short trigger gaps, breakdown of the main gap was always initiated by a streamer launched from the trigger pin before breakdown of the trigger gap.

EXPERIMENTAL SETUP

Figure 1 shows a schematic drawing of our experimental apparatus. A trigatron spark gap was placed inside a metal housing which could be evacuated and then back-filled. Gap spacing was 2.5 cm, resulting in V_{SB} = 62 kV for a 700 Torr N_2 fill. The gap was designed to appear as a 50 Ω, constant impedance transmission line. Voltage was supplied to the gap by a D.C. charged, 50 Ω, coaxial cable, and the gap discharged into a matched load. For most experiments the length of the cable was chosen to correspond to a 20 ns roundtrip transit time in order to avoid swamping the sensitive optical cameras upon arc formation. For other experiments, such as those measuring closure delay, a 120 ns cable was used. The trigger generator consisted of an 800 ns, 50 Ω, D.C. charged coaxial cable switched by a laser-triggered spark gap. The laser-triggered gap produced a pulse with a 3-4 ns risetime, but we estimate the risetime of the pulse at the trigger pin tip to be 10-20 ns because of impedance mismatches in the circuit leading into the trigatron gap. Capacitive voltage probes with ≈2 ns risetime monitored trigger pin and main gap voltages as shown in the figure. A low inductance current viewing resistor in the load provided a monitor of load current. Optical events in the gap were recorded with a high sensitivity streak camera and a locally-constructed two-dimensional shutter camera capable of about 5 ns temporal resolution.

RESULTS AND DISCUSSION

Figure 2 shows a typical sequence of two-dimensional shutter photographs of events occurring in the trigatron gap very early in the triggering process for a gap charged close to static breakdown, V_{SB}. Other conditions were as listed in the caption. The luminous objects in Figs. 2a) and 2b) are cathode-directed streamers, and are the first events optically

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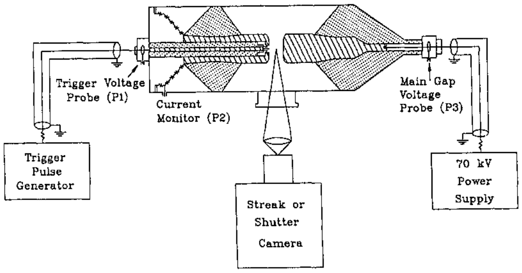

Fig. 1. Schematic diagram of the experimental setup used for the work discussed in this paper.

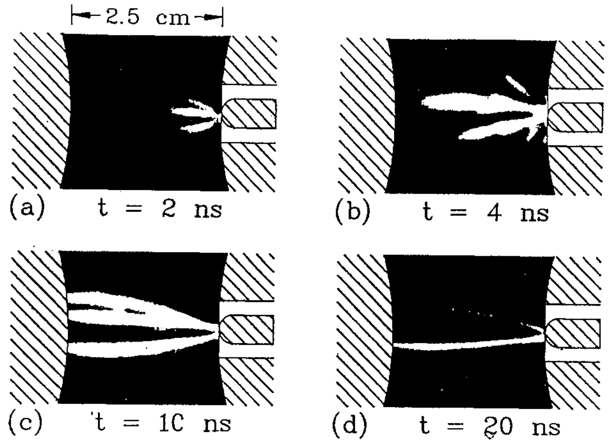

Fig. 2. Sequence of shutter photos showing the time development of cathode-directed streamers in the main gap. The streamers are pictured at various times after initiation. Due to the increasing intensity of the channels, the image intensifier gain was lower for (c) and (d). Conditions were: positive trigger, negative main gap (+-) polarity, V_t = 10 kV, V_g = -60 kV, N_2 at 700 Torr, 2.5 cm gap separation, 4.76 mm dia. trigger pin flush with the main electrode.

detectable in the gap. Several streamers are launched. These streamers have diameter of 1-2 mm, and propagate from the trigger pin tip to the distant main gap electrode, roughly following field lines, at speeds greater than 10^8 cm/sec. Upon contact with the distant electrode, gap current begins to increase markedly, and the emission from the streamer channels intensifies. Generally, one channel heats more rapidly than the others, and begets an arc connecting the trigger pin tip to the main electrode. This process is shown in Figs. 2c) and 2d). The camera sensitivity is lower in 2c) than 2b), and in 2d) than 2c). For each breakdown event only one shutter photo could be obtained with our equipment, so the photos in Fig. 2 are each from a different shot. The shutter of the camera was open for about 5 ns, comparable to the transit time for the streamers, implying that there is considerable motional blurring of the images. We obtained shutter photos similar to these for a number of pressures between 250 and 900 Torr in N_2. Shutter photos of anode-directed streamers taken with charging voltage near V_{SB} are similar to those of cathode-directed streamers, except that the anode-directed streamers have a more pinnate appearance. For lower charging voltages the appearance of the two types of streamers becomes quite different, however.

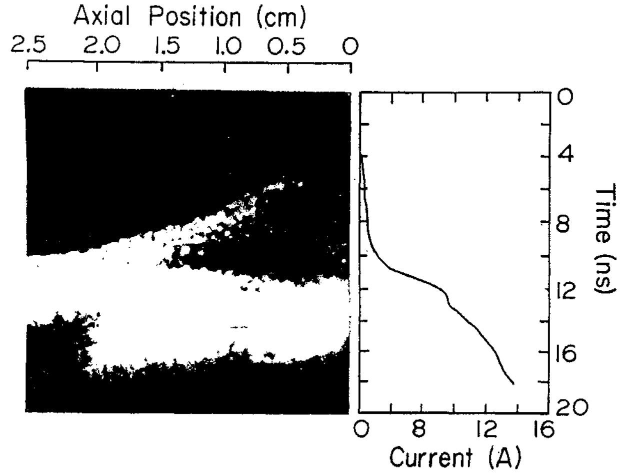

Fig. 3. Synchronized streak picture and main gap current trace, obtained under the same conditions as Fig. 2. Synchronization is accurate to within ± 1 ns.

Figure 3 shows a typical streak photograph, along with the gap current for the same shot, obtained under the same conditions as in Fig. 2. The time scales on the streak photo and the current trace are synchronized to within ±1 ns. The photo shows very clearly a luminous front resulting from a streamer crossing the gap. Starting within a few ns of the time the streamer appears at the trigger pin tip on the streamer photo, the gap current starts to rise. This current is primarily the result of the motion of free electrons inside the streamer body. The plasma of the streamer tends to shield the streamer interior from the external field, but is only partially successful because of the rapidly changing conditions produced by the propagating streamer tip.

In most cases, the gap current jumped simultaneously (±1 ns) with the streamer arriving at the opposite main gap electrode. When the streamer contacts this electrode, the requirement of constant potential drop is inconsistent with significant shielding of the main streamer body, and the field inside the streamer must rise.[20] This effect is seen in the electrical diagnostic as this current jump, and in optical diagnostics as a sudden increase in luminosity. Neglecting any voltage drop across the electrode-plasma interfaces, we estimate the resistance of the streamer channel at this time to be somewhat larger than 6 kΩ, and the average free electron density in the streamer channel to lie in the range 10^{14}-10^{15} cm^{-3}, in good agreement with theoretical expectation.[21]

Simultaneously with the process described above, the gap between the trigger pin and the adjacent main gap electrode is also undergoing a streamer-initiated breakdown process similar to that in the main gap. For triggering, it is necessary that the breakdown of the trigger gap be delayed until after a streamer has been launched and crossed some fraction of the main gap. The presence of voltage on the trigger pin probably aids the subsequent channel heating process, but it is not required.

To measure the dependence of streamer velocity on environmental parameters such as applied voltage or pressure, we measured the time required for the streamer to cross the gap as a single-number measure of velocity. We tabulated streamer transit times as a function of charging voltage over the range 35-60 kV

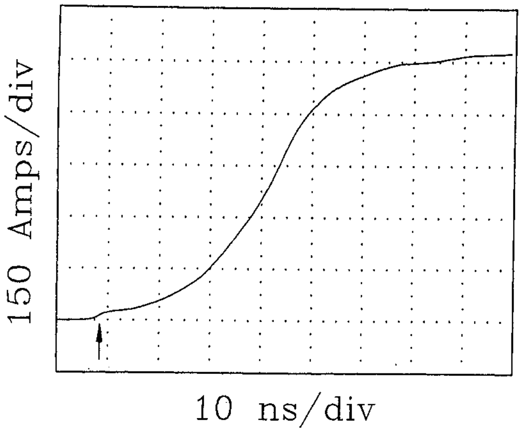

Fig. 4. Oscilloscope trace of breakdown current obtained with diagnostic P3 showing the complete breakdown process from initiation to gap closure. Conditions were the same as in Fig. 2. The current jump associated with streamer contact is marked with the arrow.

for four trigger voltages, ranging from 10 to 25 kV, and for the two heteropolar charging configurations. Plotting the data, we found that for a given trigger voltage and polarity configuration, the transit times fit a straight line fairly well, but there was considerable scatter between data sets taken with differing trigger voltages. Since the streamer velocity is a function of (among other things) the electric field ahead of it, and since the streamer consists of a conductive channel connected to the trigger pin, one might expect that the streamer velocity would be more accurately a function of the voltage difference between the trigger pin tip and the distant main gap electrode, $V_g - V_t$, than the difference between the two main gap electrodes, V_g. This point was first made by T.H. Martin.[17] Plotting vs total voltage reduced the scatter between data with differing trigger voltage substantially. We therefore conclude that the streamer data are better represented as a function of $V_g - V_t$ rather than just V_g. For the (+-) polarity (first sign the trigger polarity, second the charging polarity) the transit times varied between abut 5 ns for $|V_g - V_t| = 85$ kV to 20 ns at 45 kV. For the (-+) polarity time ranged from about 8 ns at 85 kV to 30 ns at 60 kV.

For charging voltages near V_{SB} we tabulated the gap transit times as a function of trigger pin diameter, and found the dependence to be weak. We also tabulated streamer transit time as a function of fill gas pressure for pressures between 250 and 900 Torr for charging voltages kept a fixed fraction of V_{SB}. We found that the transit time decreased with increasing pressure, changing by roughly a factor of 3 over this pressure range. These data were taken with a fixed trigger voltage, however. It probably would have been more meaningful to reduce the trigger voltage as the pressure was reduced in order to keep the trigger voltage a fixed percentage of the charging voltage. Doing so would result in a stronger dependence of streamer transit time on pressure than we found.

Fig. 4 shows an oscillogram of the main gap current in the trigatron. The current jump resulting from bridging of the gap by the streamer(s) is not as obvious in this figure as in Fig. 3 because of the reduced sensitivity, and is marked with an arrow. At this point, occurring about 5 ns after streamer initiation, the switch is still effectively open, and closure must await the formation of an arc. The arc formation time clearly exceeds the streamer transit time. In all cases we investigated we found the arc formation time to exceed the streamer transit time by a factor of 5-10.

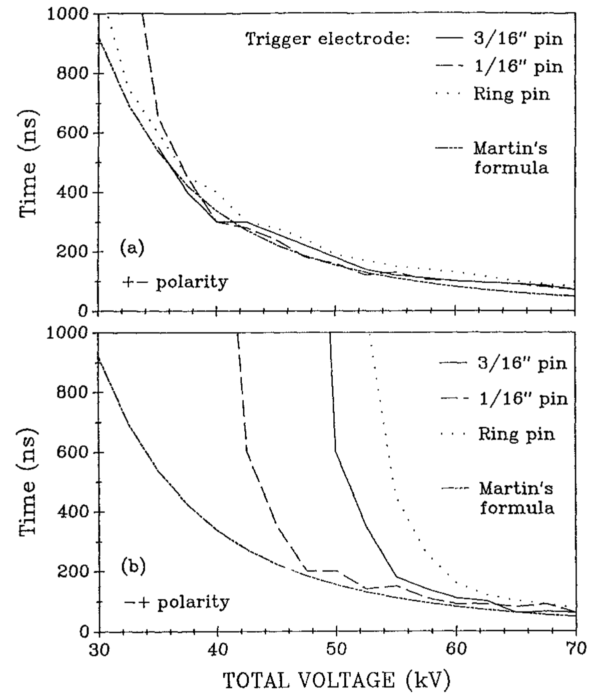

Fig. 5. Plot of arc formation times for varying trigatron gap conditions. The arc formation time was defined to be the time required after streamer contact for the gap current to rise to >95% of the steady-state value. Results are shown for several types of trigger electrode, as well as both a) positive trigger, negative main gap (+-), and b) negative trigger, positive main gap (-+) polarities. Gap conditions were otherwise the same as in Fig. 3. Also shown is the prediction of Martin's empirical formula as discussed in the text.

Fig. 5 shows the closure time (defined as the time required for the gap current to reach 95% of the final value) plotted vs. the total voltage for three different trigger pin geometries and for both heteropolar polarity configurations. At the lower charging voltages there was considerable shot-to-shot variation in the arc formation time. The data shown in these figures represent typical values of these times, subjectively averaged over about ten shots per point. As expected, the time increases with decreasing total voltage. The dependence on voltage is weak for the higher voltages, but becomes much stronger at the lower voltages. For charging voltage near V_{SB}, the closure time was about the same for both polarity configurations, and all pin types.

T.H. Martin[17] has developed a phenomenological model for breakdown based on an earlier phenomenological model by J.C. Martin.[22] Among other things, the model predicts the arc formation time for breakdown of gases at pressures around and above atmospheric. Applied to our gap, this formula is[19]

$$t = k\,\rho^{2.5}\left(\frac{d}{|V_g - V_t|}\right)^{3.5} \qquad (1)$$

where ρ is the mass density of the fill gas, t the arc formation time, d is the gap separation, and k is a constant. For ρ in g/cm^3, V_g and V_t in kV, d in cm, and t in seconds, Wells gives the constant k as $k = 1.1 \times 10^5$.[19] The times predicted by this formula for our spark gap are also shown in Fig. 5.

We measured the jitter in closing time by recording a number of main gap current traces on a storage oscilloscope, and taking the jitter to be the range of times recorded. We found the jitter to be roughly independent of total voltage down to a point, and then to increase dramatically, suggesting that there are two distinct mechanisms contributing to closing delay: the jitter of one being independent of charging voltage, and the jitter of the other being strongly voltage dependent. To determine the source of the jitter we measured separately the jitter in the time of streamer appearance at the trigger pin tip, and compared it with the overall jitter in closure. For 10 kV trigger voltage and the polarity configuration producing cathode-directed streamers, we found the jitter in streamer creation time to be 5-10 ns, nearly independent of main charging voltage over the range 25-60 kV. This jitter is probably due to the relatively slow rise time of the trigger pulse at the trigger pin tip (estimated to be 10-20 ns). The jitter in closing time also remained nearly constant at ≈15 ns over the range 40-60 kV, but increased rapidly below 40 kV. We conclude that above 40 kV charging voltage jitter was due primarily to streamer initiation, whereas below 40 kV jitter was due to fluctuations in the channel heating process. Because of the slow rise time of the voltage pulse at our trigger pin tip, we cannot determine a minimum jitter in streamer creation time. For the opposite polarity configuration (producing anode-directed steamers), we have data on streamer jitter only for charging voltages above 50 kV. In this range, the behavior was similar to that of the opposite polarity.

The shutter photos presented in Fig. 2 were taken with V_g close to V_{SB}. The situation changes dramatically with lower charging voltages. For charging voltage ≈50% of V_{SB} and (+-) polarity configuration (producing cathode-directed streamers), the streamers are thin (≈ 1 mm) and have a much more forked appearance. The streamers travel much slower than with higher charging voltage, and the trigger gap breaks down while the streamers are in transit. The channel heating phase, occurring after the streamers contact the distant main electrode, is very complex. Multiple waves of luminosity appear to propagate across the gap for several hundred ns before one channel finally begins to dominate and an arc forms, closing the gap. For the opposite polarity configuration (producing anode-directed streamers), we typically observe only a few streamers in the gap. At 66% of V_{SB}, the streamer velocity is only about twice the electron drift velocity and the streamer is much fatter (≈4 mm), consistent with the assumption that the streamer is becoming a drifting avalanche of electrons. After contact with the distant electrode the luminosity remains diffuse until the late stages of arc formation when one or two filaments form.

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